5-26-2018

Introduction to a Resources Special Issue on Criticality of the Rare Earth Elements: Current and Future Sources and Recycling

Simon M. Jowitt
University of Nevada, Las Vegas, simon.jowitt@unlv.edu

resources

MDPI

Editorial

Introduction to a Resources Special Issue on Criticality of the Rare Earth Elements: Current and Future Sources and Recycling

Simon M. Jowitt

Department of Geoscience, University of Nevada Las Vegas, 4505 S. Maryland Parkway, Las Vegas, NV 89154-4010, USA; simon.jowitt@unlv.edu; Tel.: +1-702-895-2447, Fax: +1-702-895-4064

Received: 14 May 2018; Accepted: 23 May 2018; Published: 26 May 2018

check for updates

Abstract: The rare earth elements (REE) are vital to modern technologies and society and are amongst the most important of the critical elements. This special issue of Resources examines a number of facets of these critical elements, current and future sources of the REE, the mineralogy of the REE, and the economics of the REE sector. These papers not only provide insights into a wide variety of aspects of the REE, but also highlight the number of different areas of research that need to be undertaken to ensure sustainable and secure supplies of these critical metals into the future.

Keywords: rare earth elements; criticality; critical metals; mineralogy; mineral economics

The rare earth elements (REE) are amongst the most important of the critical elements and have a wide variety of uses (Table 1) within the civilian, energy, and military sectors of the economy. These elements are defined by the International Union of Applied and Pure Chemistry (IUPAC) as the 15 lanthanide elements plus Sc and Y (Table 1) [1]. They have similar electron configurations but also have very distinctive physical and chemical properties that are ideally suited to their usage in a wide variety of technologies and industrial applications. The REE enable or enhance certain magnetic, luminescence, and strength characteristics within end-products, all of which are derived from their partially occupied 4f electron orbitals [2]. This means these elements have low substitutability and as such are crucial to a wide variety of modern and high technologies in a range of different sectors (Table 1).

Table 1. Common uses of the rare earth elements.

Element	Common Uses	Medium-Term Supply Risk	Long-Term Supply Risk
La	Optics, batteries, catalysis	64.2	46.5
Ce	Chemical applications, coloring, catalysis	63.3	44.0
Pr	Magnets, lighting, optics	65.1	49.2
Nd	Magnets, lighting, lasers, optics	64.5	47.5
Pm	Limited use due to radioactivity, used in paint and atomic batteries; very rare in nature	N/A	N/A
Sm	Magnets, lasers, masers	63.8	45.4
Eu	Lasers, color TV, lighting, medical applications	64.7	48.1
Gd	Magnets, glassware, lasers, X-ray generation, computer applications, medical applications	64.7	47.9
Tb	Lasers, lighting	64.7	47.9
Dy	Magnets, lasers	64.4	47.1
Ho	Lasers	64.4	47.2
Er	Lasers, steelmaking	64.8	48.2
Tm	X-ray generation	64.1	46.2
Yb	Lasers, chemical industry applications	64.1	46.2
Lu	Medical applications, chemical industry applications	63.9	45.7
Sc	Alloys in aerospace engineering, lighting	N/A	N/A
Y	Lasers, superconductors, microwave filters, lighting	62.8	42.1

Adapted from Weng et al. [3] with supply risk scores (out of 100, where 100 is the highest possible risk) from Nasser et al. [4]. N/A = Not available.

The increase in the number of uses of the REE has also led to a coincident increase in demand for these elements [3]. However, although abundant REE resources have been identified to date [3], it is unclear how many of these resources will be converted into reserves and production. This uncertainty reflects a wide variety of aspects such as challenges over the processing of REE ores and the presence of deleterious elements, such as Th, two of several factors that both currently and in the future may result in some REE resources (e.g., within heavy mineral sands [5]) not being utilized. Social and environmental issues and the uncertainties over the economics of the REE sector of the economy [6], among others, also contribute to the uncertainties over REE resources. The majority of REE demand is met by primary production from mines, dominantly within China (e.g., Bayan Obo). This dominance of supply from one country is an important factor in the criticality of the REE. One factor relating to this heavy reliance on the primary production of the REE is the balance problem, where the primary production is dominated by La and Ce but the majority of REE demand is for Nd or Dy [7,8]. This issue could be overcome by the recycling of REE-bearing end-products that predominantly contain Nd and Dy rather than other less-in-demand REE. However, currently less than 1% of the REE within end-products are currently recycled [9]. This lack of recycling reflects the fact that the amount of the REE used in end-products spans several orders of magnitude (<mg to several kg [10]). In addition, the recycling of the REE is hampered by the complexity of the uses of these elements, the difficulties involved in chemically separating the REE into individual elements, and the long lifetime of some of the uses of the REE, among other reasons [9].

All of this means that more needs to be known about the REE in order to ensure that secure and sustainable supplies of these critical elements are available long into the future. The papers within this special issue provide a number of new insights into different aspects of the geology of the REE, the processes that concentrate these critical elements, the potential for the extraction of these elements from unconventional sources, extraterrestrial sources of the REE that may be useful during future space exploration and exploitation, and the economics of the REE.

McLemore provides an outline of REE potential of mineralizing systems associated with the alkaline igneous rocks along the edge of the Basin and Range province, specifically focusing on the alkaline rocks of the Great Plain Margin, New Mexico, USA [11]. This N-S trending belt of alkaline magmatism is associated with crustal thickening between the Basin and Range and the Rocky Mountains and hosts Th-REE-fluorite (±U, Nb) epithermal mineralization. The gold-rich deposits in this region have moderate to low REE concentrations, although the presence of carbonatites in this region and in associated parts of Mexico suggest that there may be potential for carbonatite-hosted REE mineralization in this area [11].

Smith et al. provide an overview of the REE potential of geothermal brines, a potentially significant resource that could yield sustainable supplies of a wide variety of commodities, not just the REE [12]. The potential co-recovery of geothermal energy also makes these geothermal systems attractive targets for future exploitation. The authors provide an outline of the current state of knowledge on the distribution of the REE within geothermal brines as well as current approaches and the overall feasibility of REE recovery from these geothermal systems [12]. Their overall conclusion is that although these geothermal systems contain interesting concentrations of the REE that technically can be recovered, it is not currently economically viable nor strategically significant to pursue this approach for REE extraction [12].

The research presented by Catlos and Miller focuses on the mineralogy and composition of monazite, a light rare earth element (LREE)-bearing mineral, within the Llallagua tin deposit in Bolivia [13]. The monazite associated with the deposit contains low concentrations of radiogenic elements, a key factor in preventing this mineral being used as a source of the REE elsewhere [5]. Previous research in this area suggests that the monazite in this region formed directly from hydrothermal fluids, meaning the composition of this mineral can provide insights into the fluids that formed the deposit. The monazite at Llallagua contains more U than Th, as well as very high concentrations of F, an element that forms complexes with the REE in solution [14] and therefore potentially enables these critical elements to be mobilized. The Llallagua monazite contains high concentrations of Eu and has positive Eu anomalies, suggesting the deposit formed in a reduced back-arc environment, potentially as a result of the dissolution of pre-existing fluorapatite. All of these data indicate the usefulness of monazite as a recorder of fluid geochemistry, mineral reactions, and the tectonic settings of associated mineral deposits [13].

The paper by Chen et al. [15] also focuses on monazite, this time within carbonatite deposits, one of the world's most important sources of the REE [3]. The authors state that more than 30 known carbonatite-related REE resources are dominated by monazite, an often secondary mineral within these systems that is associated with apatite. Carbonatite-hosted monazite is geochemically variable but is dominated by the Ce-form of this mineral. These monazites are light REE-enriched, heavy REE-depleted, and are free of Eu and Ce anomalies [15]. These minerals also have Sm-Nd isotopic compositions that are similar to their host rocks, although the Th-U-Pb ages for these minerals generally yield thermal or metasomatic disturbance ages rather than primary ages for the associated carbonatite.

Another globally important set of REE resources are associated with alkaline igneous rocks [3]. Dostal [16] provides an overview of the REE deposits genetically linked with this type of magmatism, where REE mineralization is associated with differentiated rocks that range in composition from nepheline syenites and trachytes to peralkaline granites. The alkaline igneous units associated with these REE enrichments are located in continental within-plate tectonic settings. This REE mineralization is located within layered alkaline complexes, granitic stocks, and late-stages dikes, as well as more rarely within trachytic volcanic and volcaniclastic deposits. Dostal [16] indicates that the majority of alkaline igneous rock-related REE mineralization is present as accessory minerals such as bastnäsite, eudialyte, loparite, gittinsite, xenotime, monazite, zircon, and fergusonite. These minerals are concentrated during the later stages of magmatic evolution, a process that generates the REE enrichments associated with this type of magmatism. In addition, this primary REE mineralization is often remobilized and potentially enriched by late-stage magmatic–hydrothermal fluid activity [16].

McLeod and Krekeler [17] move the focus of this special issue to the Moon and beyond, focusing on potential extraterrestrial sources of the REE. Late-stage lunar magmatism generated residual melts that were enriched in K, the REE, and P (i.e., KREEP). Each of the sets of samples we have from the Moon from the Apollo and Luna missions as well as from the lunar meteorite catalogue contain accessory REE minerals such as apatite, merrillite, monazite, yttrobetafite, and tranquillityite, although lunar REE abundances are low compared to similar terrestrial samples. This indicates that it is currently unlikely that the Moon contains economically relevant abundances of the REE [17]. However, the authors suggest that this may be a result of a lack of information about the Procellarum KREEP Terrane, an area of concentrated KREEP magmatism that may yield locally elevated REE concentrations [17]. This suggests that future lunar exploration and mapping may reveal areas containing elevated concentrations of the REE. McLeod and Krekeler [17] also state that Mars and other extraterrestrial materials contain REE-bearing minerals, albeit at low modal abundances. This indicates that these materials may potentially be sources for the REE as a by-product of the production of other commodities vital to space exploration and utilization [17].

The last paper in the special issue, by Macachek et al. [18], focuses on how the REE fit into a circular economy model whereby resources are kept in use for as long as possible before being recycled into new end-products, ensuring the most is made of the REE originally derived from primary sources. The authors present an overview of the risk and value challenges connected to closing value chain loops and the development of a circular economy within the REE sector [18]. This paper presents a new analytical framework and provides several case studies of loop closure within the REE industry. Macachek et al. [18] also identify how risk–value relationships are constructed and how these can impact the closure of REE value chain loops, or rather what prevents these loops being closed as a result of the different motivations of industry and government agencies. The authors conclude that governments need to mediate against the construction of risk–value relationships by facilitating the generation of information on end-of-life materials. This would enable the REE sector to more effectively transition into a circular economy, rather than remaining in the current situation where, for example, only very limited amounts of the REE present in end-products are recycled [9].

These papers not only provide insights into a wide variety of aspects of the REE, but also highlight that research needs to continue into various aspects of the REE to ensure we make the most of the resources of these critical metals.

Acknowledgments: I thank the reviewers who provided constructive reviews of all of the papers within this special issue, enabling the timely production of this issue of Resources. I would also like to thank Damien Giurco and the Resources editorial board for the chance to put this special issue together.

Conflicts of Interest: The author declares no conflict of interest.

References

1. IUPAC. *Nomenclature of Inorganic Chemistry—IUPAC Recommendations*; International Union of Pure and Applied Chemistry (IUPAC): Cambridge, UK, 2005.
2. Izatt, R.M.; Izatt, S.R.; Bruening, R.L.; Izatt, N.E.; Moyer, B.A. Challenges to Achievement of Metal Sustainability in Our High-Tech Society. *Chem. Soc. Rev.* **2014**, *43*, 2451–2475. [CrossRef] [PubMed]
3. Weng, Z.; Jowitt, S.M.; Mudd, G.M.; Haque, N. A Detailed Assessment of Global Rare Earth Resources: Opportunities and Challenges. *Econ. Geol.* **2015**, *110*, 1925–1952. [CrossRef]
4. Nassar, N.T.; Du, X.; Graedel, T.E. Criticality of the rare earth elements. *J. Ind. Ecol.* **2015**, *19*, 1044–1054. [CrossRef]
5. Mudd, G.M.; Jowitt, S.M. Rare earth elements from heavy mineral sands: Assessing the potential of a forgotten resource. *Appl. Earth Sci.* **2016**, *125*, 107–113. [CrossRef]
6. Sykes, J.P.; Wright, J.P.; Trench, A.; Miller, P. An assessment of the potential for transformational market growth amongst the critical metals. *Appl. Earth Sci.* **2016**, *125*, 21–56. [CrossRef]
7. Binnemans, K.; Jones, P.T. Rare Earths and the Balance Problem. *J. Sustain. Metall.* **2015**, *1*, 29–38. [CrossRef]
8. Elshkaki, A.; Graedel, T.E. Dysprosium, the Balance Problem, and Wind Power Technology. *Appl. Energy* **2014**, *136*, 548–559. [CrossRef]
9. Jowitt, S.M.; Werner, T.T.; Weng, Z.; Mudd, G.M. Recycling of the Rare Earth Elements. *Curr. Opin. Green Sustain. Chem.* **2018**, *13*, 1–7. [CrossRef]
10. Binnemans, K.; Jones, P.T.; Blanpain, B.; van Gerven, T.; Yang, Y.; Walton, A.; Buchert, M. Recycling of Rare Earths: A Critical Review. *J. Clean. Prod.* **2013**, *51*, 1–22. [CrossRef]
11. McLemore, V.T. Rare earth elements (REE) deposits associated with great plain margin deposits (alkaline-related), southwestern united states and eastern Mexico. *Resources* **2018**, *7*, 8. [CrossRef]
12. Smith, Y.R.; Kumar, P.; McLennan, J.D. On the Extraction of Rare Earth Elements from Geothermal Brines. *Resources* **2017**, *6*, 39. [CrossRef]
13. Catlos, E.J.; Miller, N.R. Speculations Linking Monazite Compositions to Origin: Llallagua Tin Ore Deposit (Bolivia). *Resources* **2017**, *6*, 36. [CrossRef]
14. Migdisov, A.A.; Williams-Jones, A.E.; Wagner, T. An experimental study of the solubility and speciation of the Rare Earth Elements (III) in fluoride-and chloride-bearing aqueous solutions at temperatures up to 300 C. *Geochim. Cosmochim. Acta* **2009**, *73*, 7087–7109. [CrossRef]
15. Chen, W.; Honghui, H.; Bai, T.; Jiang, S. Geochemistry of Monazite within Carbonatite Related REE Deposits. *Resources* **2017**, *6*, 51. [CrossRef]
16. Dostal, J. Rare Earth Element Deposits of Alkaline Igneous Rocks. *Resources* **2017**, *6*, 34. [CrossRef]
17. McLeod, C.L.; Krekeler, M.P. Sources of Extraterrestrial Rare Earth Elements: To the Moon and Beyond. *Resources* **2017**, *6*, 40. [CrossRef]
18. Machacek, E.; Richter, J.L.; Lane, R. Governance and Risk-Value Constructions in Closing Loops of Rare Earth Elements in Global Value Chains. *Resources* **2017**, *6*, 59. [CrossRef]